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Magnetic orientation of sisal fibers in cementitious matrix: mechanical behavior and image analysis

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Abstract

Abstract. This work presents the preliminary results of an experimental investigation focused on the magnetic orientation of natural sisal fibers embedded in a cementitious matrix. The objective of this research is to evaluate the effect of magnetic orientation of sisal fibers on the mechanical behavior of thin cementitious plates tested under flexion. In the first phase, the work addresses the development of a coating which is applied to short sisal fibers in order to provide their magnetic alignment. The second phase is focused on the methodology employed for the magnetic orientation of the reinforcement. The final phase involves the mechanical characterization and image analysis (radiography and calculation of the fiber orientation factor) of the cementitious composites. The results indicated that the magnetic alignment of sisal fibers in cementitious matrix is possible and contributes to the composite flexural performance.

Keywords: Sisal fibers. Magnetic alignment. Mechanical behavior. Radiography.

1. INTRODUCTION

Natural fibers, such as sisal, have been used as reinforcement in fragile matrices for more than two millennia [1]. One of the most classic examples is the manufacture of adobe bricks, which use vegetable straw as reinforcement. The natural fibrous reinforcement, whether random or aligned in one or more directions, is able to provide the fragile matrix with some post-cracking ductility, as well as generous increases in the load capacity when subjected to tension (> 170%) and bending (> 180%) [2,3].

The effectiveness of sisal reinforcement in cementitious matrices, however, depends on a large chain of factors. Among them, it is possible to quote: the reinforcement volume fraction, fiber length, surface treatments applied to the fibers (e.g.: peeling, coatings, saturation in water or pozzolana), methods of production and curing of the composites (e.g.: carbonation and application of static molding pressure). Above all, it is worth to mention the "orientation of the fibrous reinforcement", focus of the present study [4].

When aligned in the loading direction, sisal fibers provide to the cementitious composites high toughness, tensile strength and flexural strength [5,6]. The orientation of sisal reinforcement, however, only becomes elementary in the case of the use of textiles. When used in the form of short fibers (most common case), the reinforcement remains random, which ends up reducing the potential mechanical performance of the resulting composites.

One of the most effective ways to align fibrous reinforcement in cementitious matrices is the use of magnetic fields [7,8,9]. This technique, however, is only applicable to metallic fibers, or fibers coated with metallic material. Recent studies indicate that the use of simple magnetic circuits or magnets can significantly increase the degree of orientation of the fibrous reinforcement in cementitious matrices, resulting in significant increases on the mechanical performance [7,8,9].

Bringing this innovative technology to the field of composites reinforced with natural fibers, the aim of this research is to evaluate the effect of magnetic orientation of sisal fibers on the mechanical behavior of thin cementitious plates subjected to bending tests. In the first phase, the work addresses the development of a coating (with epoxy adhesive and ferromagnetic particles) which is applied to short sisal fibers in order to provide their magnetic alignment. The second phase is focused on the methodology employed for the magnetic orientation of the reinforcement. The final phase involves the mechanical characterization and image analysis (radiography and calculation of the fiber orientation factor) of the cementitious composites.

2. MATERIALS AND METHODS

2.1. Components of the matrix and mix design

The matrix used in this work was produced from a High Early Strength Portland Cement CPV ARI (from Liz Cimentos Co.) and limestone filler (from Hocim Co.) using the following mass formulation: 1:1:1 (cement: sand: water). Such matrix, common in fiber cements, was produced with the aim of ensuring enough workability to provide the torque of the fibers under the action of the magnetic field. Prior to production of composites, the mixture of components was carried out in a planetary mixer (from Solotest Co.) during 3 min.

2.2. Reinforcement and surface treatment

The sisal fibers used in this research were supplied by Sisal Sul Co. in packs of 1 kg and approximately 1 m long. Before mixing, all sisal fibers were subjected to an untangling process (Figure -a), giving rise to the fibers called, in this study, "*in natura*" (Figure -b). After this stage, part of the fibers was subjected to a surface treatment using an epoxy-based adhesive and metal cutting residue (Figure 1-c and Figure 1-d). The length of the fibers and the fiber volumetric fraction (Vf) used in all composites were kept, respectively, at 10 mm and 0.56%. For surface treatment, only ferromagnetic particles smaller than 300 µm were used. This material was obtained through sieving and magnetic classification of metal cutting waste. The adhesion of the ferromagnetic material to the reinforcement was performed through an epoxy adhesive applied manually to the surface of the fibers. After coated with adhesive, the fibers were gently covered with metallic particles for about 1 min. Once the adhesive was dry (~ 4h), the fibers were cut and packaged for later use as fibrous reinforcement. The mass ratio between ferromagnetic material (mFe) and fiber mass (mf) used in the surface treatment was ~11. More details about the definition of fiber length, Vf, surface treatment and matrix rheological parameters can be found in the preliminary work developed by Freitas [10].

(a) (b) (c) (d)

Figure 1 – Surface treatment applied to the sisal fibers: (a) Untangling process, (b) fibers "*in natura*", (c) adhesion of ferromagnetic residue to fibers and (d) treated fibers before cutting.

2.3. Materials and equipment used in fiber orientation Acrylic formwork

All specimens were produced in acrylic molds with dimensions of 400 mm x 240 mm x 13 mm. Styrofoam dividers were then employed in order to generate specimens of 240 mm x 50 mm x 13 mm.

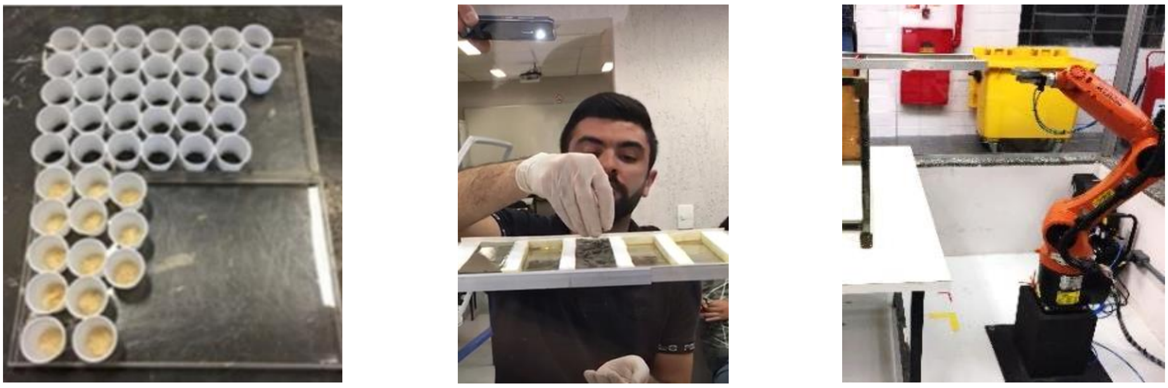
The choice for acrylic and styrofoam was due to the properties of both materials, which should not interfere with the generated magnetic field.

Neodymium magnets and robot

In order to guarantee uniformity in the production of the composites, the alignment of the fibers was carried out by neodymium magnets coupled to a computer-controlled industrial robot. The fiber alignment technique proposed in this study was based on the movement of the neodymium magnets under the molds (containing matrix and treated fibers) [10]. For this, two neodymium magnets (model N50), supplied by New Imãs Indústria e Comércio Co., were used. The alignment process was controlled by a KUKA industrial robot, model KRC 900, with 6 kg load capacity and 2 m/s maximum speed. The trajectory of the magnets was directed along the largest dimension of the specimens (240 mm). The start, return and end points were positioned 10 cm away from the specimens.

2.4. Composites manufacturing and curing process

With four acrylic molds (divided in five parts), four different types of cementitious composites were produced (Figure 2). The nomenclature and specific characteristics of each produced composite are presented, respectively, in Table 1 and Table 2. In the adopted nomenclature, the following abbreviations are used: CC for cementitious composite, S for sisal fiber, IN for *in natura*, RA for randomly arranged, T for treated (fibers with surface treatment) and OR for oriented.



(a) (b) (c)

Figure 2 – Magnetic orientation of sisal fibers: (a) Reinforcement dosage, (b) reinforcement placement and (c) magnetic alignment of fibers.

As reported on Table 1, the composites were developed with and without magnetic fiber orientation. The molding methodology for each type of composite is described in Table 3. The different employed techniques result from the specific characteristics of each composite (i.e.: orientation, presence of fibers and type of reinforcement). The magnets were moved under the forms at a displacement speed of 7 cm/s. The distance established between the magnets and the moulds was 5 mm.

Table 1 – Nomenclature of the produced composites.

Nomenclature	Composite features
Matrix	Cementitious matrix without reinforcement
CC_S_IN_RA	Cementitious composite reinforced with sisal fibers (*in natura*) randomly arranged
CC_S_T_RA	Cementitious composite reinforced with treated sisal fibers randomly arranged
CC_S_T_OR	Cementitious composite reinforced with treated and oriented sisal fibers

Table 2 – Fiber content present in each type of composite per specimen.

Nomenclature	Vf (%) *in natura*	Mass of fibers (g)	Mass of fibers + surface treatment (g)
Matrix	0	0	0
CC_S_IN_RA	0.56	0.78	-
CC_S_T_RA	0.56	0.78	15
CC_S_T_OR	0.56	0.78	15

Table 3 – Nomenclature and molding process for each type of composite.

Nomenclature	**Steps**	**Elapsed time (s)**	**Molding process**
Matrix	1	30	Placement of 1/2 of the matrix mass
	2	30	Placement of 1/2 of the matrix mass + surface finish
CC_S_IN_RA	1	30	Placement of 1/3 of the matrix mass
	2	30	Placement of 1/2 of the fiber mass + surface finish
	3	30	Placement of 1/3 of the matrix mass
	4	30	Placement of 1/2 of the fiber mass + surface finish
	5	30	Placement of 1/3 of the matrix mass + surface finish
CC_S_T_RA	1	30	Placement of 2/3 of the matrix mass
	2	180	Placement of 1/6 of the fiber mass + surface finish
	3	6 x 180	Step 2 is repeated 6 times
	4	30	Placement of 1/3 of the matrix mass + surface finish
CC_S_T_OR	1	30	Placement of 2/3 of the matrix mass
	2	180	Placement of 1/6 of the fiber mass + 4 movements of the magnet under the mold + surface finish
	3	6 x 180	Step 2 is repeated 6 times
	4	30	Placement of 1/3 of the matrix mass + surface finish

Once the molding and alignment process was completed, all composites were subjected to wet curing in a fog room at 25°C for 28 days.

2.5. Mechanical tests

The flexural tests were carried out in an EMIC universal testing machine, with 200 kN capacity, at 28 days of age. The span used between supports and loading point was respectively, 210 mm and 70 mm. The tests were controlled by the actuator displacement at a rate of 1 mm/min. The deflections of the plates at the mid-span were measured using an EMIC displacement transducer, up to 12 mm.

2.6. Image analysis

X-ray images were taken of all produced composites (largest specimen area, 240 mm x 50 mm) to assess the fiber orientation. Since the matrix radiography is an unusual procedure, the machine was adjusted for chest evaluation, with exposure time t = 0.05 s, at a current of 200 mA (milliampères) and a voltage of 68 kV.

To determine the fiber orientation factor along the specimens, radiographic images of the composites CC_S_T_RA and CC_S_T_OR, were treated using the software AutoCAD. Each sample was divided into 42 quadrants of around 17 mm x 16 mm. After that, five visible fibers were selected from each quadrant, totaling 210 fibers per specimen. The angle established between the fiber and the magnets direction was then determined. The fiber orientation factor was calculated to be 0 for angles equal to 90 ° and 1 for angles equal to 0 °. Finally, for each quadrant an average orientation factor was determined.

3. DISCUSSION AND ANALYSIS

3.1. Mechanical tests and image analysis

Figure 3 presents one typical curve obtained in the four-point bending tests for each composite investigated in the present work. The results of evaluation of all curves are given in Table 4. All composites reinforced with sisal fibers presented a deflection softening behavior with a single crack formation. Although both surface treatment and magnetic alignment have contributed to modify the flexural behavior of the produced composites, such effect was not enough to allow deflection hardening. This behavior is in great part related to the low Vf employed as reinforcement on the studied composites (0.56%).

The lowest flexural performance was observed for the composite CC_S_IN_RA. This pattern results from the random orientation of the reinforcement as well as the characteristic low adhesion, and consequent interfacial debonding, occurred between natural sisal fibers and matrix under tension [11]. The hydrophilic nature of the sisal reinforcement is largely responsible for the latter effect. When mixed to the matrix, sisal fibers become reservoirs of water which is subsequently released for both hydration and environment. Such wetting and drying cycle generates debonding along the surface of the fibers. As a result, low post-cracking performance is observed.

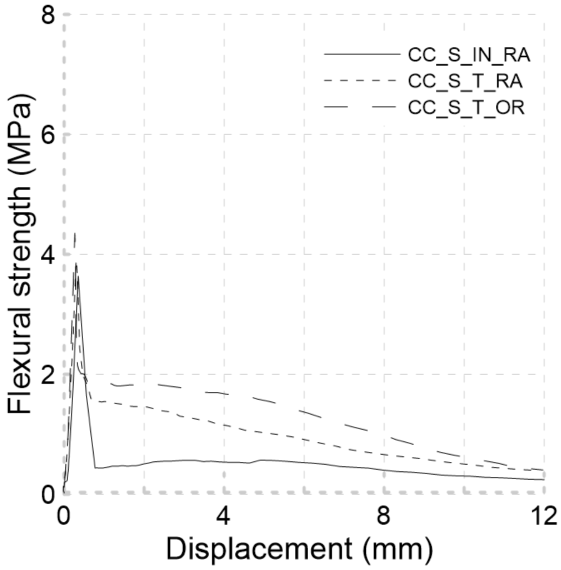


Figure 3 – Typical stress-displacement curves obtained for the cementitious plates reinforced with sisal fibers.

Table 4 – Average results of four-point bending tests. Standard deviation values are presented in parentheses.

Nomenclature	**First crack strength**		**Toughness**		
	σ (MPa)	**δ (mm)**	**T_{4mm} (J)**	**T_{8mm} (J)**	**T_{12mm} (J)**
Matrix	4.80 (1.24)	0.30 (0.06)	-	-	-
CC_S_IN_RA	4.12 (0.71)	0.33 (0.08)	3.20 (0.76)	5.24 (1.14)	6.60 (1.50)
CC_S_T_RA	4.61 (0.32)	0.26 (0.10)	6.16 (0.61)	9.90 (1.22)	11.98 (1.40)
CC_S_T_OR	5.13 (0.43)	0.35 (0.09)	6.91 (0.83)	13.55 (3.85)	14.70 (1.59)

Observing the composite CC_S_T_RA, it is possible to notice an increase of more than 80% on the accumulated toughness (up to 12 mm). Such result indicates that the treatment using ferromagnetic particles was capable to improve fiber-matrix interaction. Previous studies carried out by Freitas [10], show that in addition to the obvious increase in specific surface area provided by ferromagnetic particles, the epoxy coating ends up shielding the sisal reinforcement, generating a water absorption 87% lower in the coated fibers. In this way, not only the adhesion characteristics are improved, but probably the drying shrinkage of fibers is reduced.

The highest flexural behavior was observed for the composite CC_S_T_OR. The toughness computed as the total area under the load displacement curve showed to be, respectively, 1.2 and 2.2 times greater than that observed for the composites CC_S_T_RA and CC_S_IN_RA. This behavior results from the improvements related to fiber-matrix interaction and also the reinforcement orientation (see Figure 4), respectively.

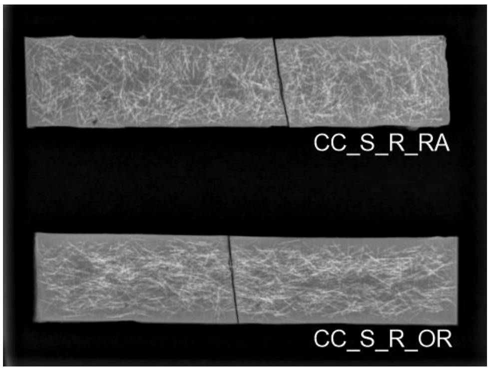


Figure 4 – Radiographic images of CC_S_T_RA and CC_S_T_OR specimens.

Figure 5 shows 2D maps of the average orientation factor calculated for two specimens produced from CC_S_R_RA and CC_S_R_OR. The average orientation factor of each quadrant was positioned at its center. A color scale was used to represent the level of fiber orientation. It is important to point out that the direction of the magnets during orientation process followed the largest dimension of the specimens.

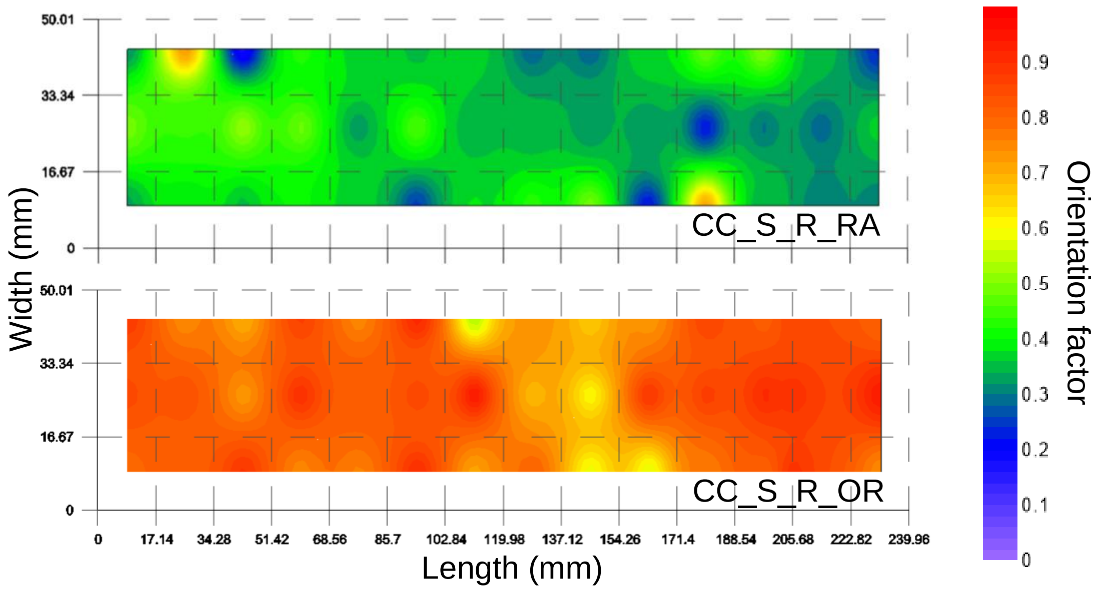


Figure 5 – Orientation factor obtained for CC_S_T_RA and CC_S_T_OR specimens.

In both composites it is possible to observe a relatively stable fiber orientation level. In case of CC_S_T_OR, a preferential fiber orientation was clearly noticed. Considering all specimens and all analyzed quadrants, the average orientation factor for the composite CC_S_T_OR was 0.794. In contrast, the composite CC_S_R_RA showed an average orientation factor of only 0.316.

4. CONCLUSIONS

The following conclusions may be drawn from the experimental campaign conducted:

The magnetic alignment method proposed in the study was able to generate a preferential orientation in the sisal fibers treated with ferromagnetic particles when embedded in a fluid cementitious matrix. The image analyses confirm this observation.

The treatment using epoxy adhesive and ferromagnetic particles was capable to improve the flexural performance of the studied composites. The comparison between composites with random fibers, coated and uncoated, confirm this observation.

The magnetic orientation of the fibers was able to promote increases in the flexural performance of the studied composites. The stress-displacement curves and toughness data confirm this observation.

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REFERENCES

Swamy, R.N. Fibre Reinforcement of Cement and Concrete. *Mat. and Constr.* (1975) 8: 235-254. https://doi.org/10.1007/BF02475172M.

Silva, F. de A., Mobasher, B. & Filho, R. D. T. Cracking mechanisms in durable sisal fiber reinforced cement composites. *Cem. Concr. Compos.* (2009). https://doi:10.1016/j.cemconcomp.2009.07.004

Toledo. R. D. Materiais compósitos reforçados com fibras naturais: caracterização experimental. Phd Thesis, DEC-PUC-Rio / DEC-Imperial College-Londres, Rio de Janeiro, 1997.

Bentur, A., Mindess, S. Fibre reinforced cementitious composites. England: Elsevier Applied Science; 1990.

Melo Filho, J.A. Desenvolvimento e caracterização de laminados cimentíceos reforçados com fibras longas de sisal. Master's thesis, UFRJ, Rio de Janeiro, 2005.

Silva, F. A.; Toledo Filho, R. D.; Melo Filho, J. A.; Fairbairn, E. M. R. Physical and Mechanical Properties of Durable Sisal Fiber-cement Composites. *Constr. Build. Mater.* (2010) 24, 777_785.

Brito, I.S.; Rambo, D.A.S; Martini, S.; Salvador, R.P.S; Freitas, M.F.M. Flexural behavior of HPFRCC: Enhancing post-crack strength and toughness by magnetic alignment of the reinforcement. *Constr. Build. Mater.* (2021) 269, 121265. https://doi.org/10.1016/j.conbuildmat.2020.121265

Gou, H.; Zhu, H.; Zhou, H.; Yang, Z. Reinforcement mechanism of orientally distributed steel fibers on ultra-high-performance concrete. *Constr. Build. Mater.* (2021) 281, 122646. https://doi.org/10.1016/j.conbuildmat.2021.122646.

Mu, R.; Diao, C.; Liu, H. Design, preparation and mechanical properties of full-field aligned steel fiber reinforced cementitious composite. *Constr. Build. Mater.* (2021) 272, 121631, 2021. https://doi.org/10.1016/j.conbuildmat.2020.121631

Freitas, M. F. M. Desenvolvimento de processo de alinhamento magnético de fibras curtas de sisal em matriz cimentícia e influência no comportamento mecânico. Master's thesis, São Judas Tadeu University, São Paulo, 2020.

Santos, S.F.; Teixeira, R.S.; Savastano, H. Interfacial transition zone between lignocellulosic fiber and matrix in cement-based composites, In: Sustainable and Nonconventional Construction Materials using Inorganic Bonded Fiber Composites, 2017. https://doi.org/10.1016/B978-0-08-102001-2.00003-6.